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An Investigation of
THE EFFECTS OF STRESS CONCENTRATION AND TRIAXIALITY ON THE PLASTIC FLOW OF METALS

Technical Report No. 26

NOTCH SENSITIVITY OF STEELS

By

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Conducted By
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ABSTRACT

The portion of room temperature notch brittleness of a high strength steel which can be attributed to transition temperature behaviors was determined. An extrapolation of the super-transition temperature branch of the notched tensile ductility vs. testing temperature curve to room temperature indicated that practically all of the embrittlement resulted from a shift in the transition temperature.

* This paper is based upon a portion of a research program conducted in the Metals Research Laboratory, Department of Metallurgical Engineering, Case Institute of Technology, Cleveland, Ohio in cooperation with the Office of Naval Research, U. S. Navy.

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NOTCH SENSITIVITY OF STEELS

INTRODUCTION

Abrupt changes of section size in structural members, or their laboratory counterpart, notches in test bars, are known to impair mechanical performance. Although the ductility and toughness of all metals are reduced by notching, these property losses seem to be disproportionately large for high strength steels. In Fig. 1, for example, the ductility (contraction in area) of SAE 1340 steel at a strength level of 150,000 psi is decreased from about 62 to about 12 per cent (reduced to about 1/5th) by the addition of an extremely sharp notch. This same notch shape reduces the ductility at a strength level of 250,000 psi from about 54 to less than 0.5 per cent (reduced to approximately 1/100th).

Notching a section subjected to a tensile load produces a stress concentration (of the longitudinal stress) and introduces transverse tensile stresses in the other two perpendicular directions. The magnitude of both the initial stress concentration and the induced transverse tensile stresses depend only on the geometry of the notch (1) (2), and hence are the same for all materials. Hence, the extraordinary high notch sensitivity of high strength steel must be a result of some secondary effect of the notch.

In a recent survey on notch toughness, the author showed that the excessive notch sensitivity of high strength steels was not apparent when the notch test was made at an elevated temperature (3). Notches

are known to elevate the temperature at which steels change abruptly from ductile to brittle (their transition temperature) (4). Therefore, since high strength martensitic steels exhibit a high transition temperature compared to the same steel at lower strength levels, it seems reasonable to suppose that at least a portion of the excessive notch sensitivity at high strength levels is a result of raising the transition temperature by the notch.

The present investigation was undertaken, consequently, in order to determine the portion of the room temperature notch sensitivity in high strength steels that is produced by a shift of the transition temperature.

MATERIAL AND PROCEDURE

The low alloy steel SAE 1340 was selected for this investigation since a considerable amount of mechanical test data were already available on this same heat of material. The steel was available in the form of 3/4 inch diameter hot rolled rods from which specimens were prepared according to the following schedule:

Normalize at 1675°F (954°C) for 1/2 hours, air cool.

Stress relieve at 1200°F (650°C) for 4 hours, furnace cool.

Rough machine to the shapes shown in Fig. 2.

Austenitize at 1525°F (830°C) for 45 minutes, oil quench.

Temper at various temperatures for one hour, water quench.

Finish machine to the dimensions shown in Fig. 2.

The mildly contoured specimens were used to determine the unnotched transition temperature for the steels used. It can be seen in Fig. 4 that mechanical properties obtained on these contoured specimens is within a few per cent of the values obtained on cylindrical test bars.

All notched specimens had a 60° notch angle, a notch radius less than 0.001 inch and a specimen diameter at the notch bottom of 0.212 inch. The specimens were completely heat treated before machining the notch. An earlier investigation on this same heat of steel showed it to harden completely in these section thicknesses (5).

All tests were conducted with the aid of a specially designed fixture which yielded an eccentricity of less than 0.001 inch. This equipment and the testing procedure have been previously described (6). The speed of testing was made to correspond to a rate of travel of the testing machine head of approximately 0.04 to 0.05 inch per minute.

RESULTS AND DISCUSSION

The dependence of notch strength and notch ductility on notch depth* for the steels tempered at temperatures between 400 and 900°F

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* Notch strength is defined as: $\dfrac{\text{maximum load in a notched test}}{\text{original cross-sectional area at notch bottom}}$

Notch duct. is defined as: $\dfrac{(\text{orig. area at notch bottom}) - (\text{fract. area at notch bottom})}{(\text{original area at notch bottom})}$

Notch depth is defined as: $\dfrac{(\text{area of unnotched cylind. section}) - (\text{area at notch bottom})}{(\text{area of cylindrical section})}$

are shown in Figs. 3 and 4. Since the maximum load strain is approximately constant for the notched bars tempered at any constant temperature (1), and since the condition of plasticity requires an increased longitudinal stress to sustain flow with transverse tensile stresses acting, the notch strength rises continuously with increasing notch depth so long as the notch ductility is sufficiently high to permit necking (1). As was previously reported (7) the notch strength shows a linear dependence on notch depth for the higher tempering temperatures. The rate at which the strength increases however is somewhat less than the previously reported rate which produced an extrapolated notch strength equal to twice the unnotched strength for a 100 per cent notch.

Because the notch strength is dependent on the notch ductility, and its behavior can be readily rationalized from the ductility behavior (3), an analysis of notch sensitivity is simplified if the effect of notches on ductility changes rather than on strength changes are considered. A convenient criterion for notch sensitivity, based on ductility, is the rate at which the ductility decreases with increasing notch depth.

It is apparent from Fig. 4 that the rate of notch damage is rather low for the steel tempered at the highest temperature (900°F). Lowering the tempering temperature increases the rate at which the ductility decreases until at a tempering temperature of 600°F even the very shallow notches are extremely harmful. Lowering the tempering temperature from 600°F to 400°F produces an improvement in the notch ducility behavior. This well-known 600°F embrittlement is readily apparent in the summary of these curves shown in Fig. 5.

The unnotched ductility, as shown by the background curve in Fig. 5, (notch ductility vs tempering temperature at zero notch depth) increases with increasing tempering temperature. Since notch damage in this study is defined as the rate at which notching decreases ductility, compensation must be made for this unnotched ductility difference. If it is assumed that the steel tempered at 900°F is notch insensitive*, the rate of notch damaging of steels tempered at lower temperatures can be compared with this basic behavior as shown in Fig. 6. The heavy curves in Fig. 6 represents the experimental data curves taken from Fig. 4, while the light curves in Fig. 6 were drawn proportional to the 900°F temper curve and in such a fashion that the two curves in each chart intersect the ordinate at the same value. Since it is assumed that the steel quenched and tempered at 900°F is notch insensitive, the excessive notch damage is given by the area bounded by these two curves.

In order to determine the portion of notch embrittlement which could be attributed to the transition temperature changes caused by notching, tensile specimens quenched and tempered at 900, 700 and 600°F, were tested in tension over a range of temperatures in an unnotched and a mildly notched (six or ten per cent) condition. These data, Figs. 7, 8 and 9, yielded the transition temperature for each steel and notch condition investigated as well as at least a section of the super-

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* This assumption seems valid since the rate at which the ductility drops for the steel tempered at 900°F is the same as that found for the aluminum alloy 24S-T4 which is thought to be notch insensitive (8).

transition branch of the ductility-testing temperature curves. It is to be seen in these figures that all the notch conditions which produced an excessively brittle behavior (the six and ten per cent notches in the steels tempered at 600 and 700°F) exhibited a transition temperature above room temperature.

The portion of the room temperature notch embrittlement resulting from the shifted transition temperature was determined by extrapolation of the ductile branch of the ductility-testing temperature curves back to room temperature. These extrapolated ductility values are added to Fig. 6. Apparently the enormous difference between the safe notch behavior of the steels tempered to a low strength level as compared with steels tempered to high strength levels is the result of a transition temperature embrittlement. It is appreciated that sufficient data are not available to establish accurate extrapolations in Figs. 7 to 9 so that this embrittlement may not be entirely a transition temperature effect, but certainly a major portion of the embrittlement must be so considered.*

The specimens quenched and tempered at 900°F exhibited a transition temperature curve whose knee was at room temperature. Presumably then, the specimens with notches deeper than ten per cent suffer some ductility loss due to the transition temperature effect, and in the

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* It should be noted that Read, Marcus and McCaughey found the strain hardening exponent of quenched and tempered steels to go through a minimum at the same tempering temperatures that produce the toughness minimum (9).

absence of this phenomenon, the steel at a strength level of 170,000 psi would presumably be even less notch sensitive than indicated in Fig. 4.

In order to obtain more accurate extrapolations of the type shown in Figs. 7 and 8, attempts were made to obtain the transition temperatures on specimens with very shallow notches. These test bars however, frequently necked outside of the notched section so that the notch ductility became dependent on the distance between the necked section and the notch. Consequently, these test results were abandoned.

Furthermore, transition temperatures were not obtained on specimens with notches deeper than ten per cent since the difference between super-and sub-transition temperature ductility for these specimens is too low to allow for an accurate determination of transition temperature.

Since excessive notch sensitivity is a result of the ability of notches to raise the transition temperature of materials, it is not surprising to find the face-centered cubic metals safe in the presence of even very severe service conditions since this class of metals is thought to never exhibit a transition temperature. (Although as a general rule face-centered cubic metals do not exhibit a transition temperature, McLean (10) has recently shown such a behavior in a series of copper-antimony alloys).

In summarizing it might be stated at least a large portion of the excessive room temperature notch sensitivity of high strength steels is a result of the fact that notches shift the transition temperature of the steels to above room temperature.

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BIBLIOGRAPHY

1. H. Neuber, "Theory of Notch Stresses: Principles for Exact Stress Calculation", Verlag J. Springer, Berlin 1937.

2. G. Sachs and J. D. Lubahn, "The Effect of Triaxiality on the Technical Cohesive Strength of Steels", J. Applied Mechanics, Vol. 12 (1945) p. 211.

3. E. J. Ripling, "How to Determine Toughness of Steels from Notched Bar Tests", Material and Methods, Vol. 34 No. 3, Sept. 1951, p. 81.

4. P. G. Jones and W. J. Worley, "An Experimental Study of the Influence of Various Factors on the Mode of Fracture of Metals", Proceedings, ASTM, Vol. 48 (1948), p. 645

5. E. J. Ripling and W. M. Baldwin, Jr., "Overcoming Rheotropic Brittleness: Precompression vs. Pretension", Trans. ASM, Vol. 44 (1952), p. 1047.

6. G. Sachs, J. D. Lubahn and L. J. Ebert, "Notch Bar Tensile Test Characteristics of Heat Treated Low Alloy Steels", Trans. ASM, Vol. 33 (1944), p. 340.

7. G. Sachs, J. D. Lubahn and L. J. Ebert, "The Effect of Notches of Varying Depth on the Strength of Heat Treated Low Alloy Steels", Trans. ASM, Vol. 34 (1945), p. 514.

8. A. W. Dana, E. L. Aul and G. Sachs, "The Effect of Triaxial Stress States on the Fracturing Characteristics of 24ST", NACA Technical Note No. 1830, March 1949.

9. T. A. Read, H. Marcus and J. M. McCaughey, "Plastic Flow and Rupture of Steel at High Hardness Levels", Fracturing of Metals, ASM 1948. Cleveland, Ohio, p. 228.

10. D. McLean, "The Embrittlement of Copper-Antimony Alloys at Low Temperatures", Journal Inst. of Metals, Vol. 81 (1952-53), p. 21.

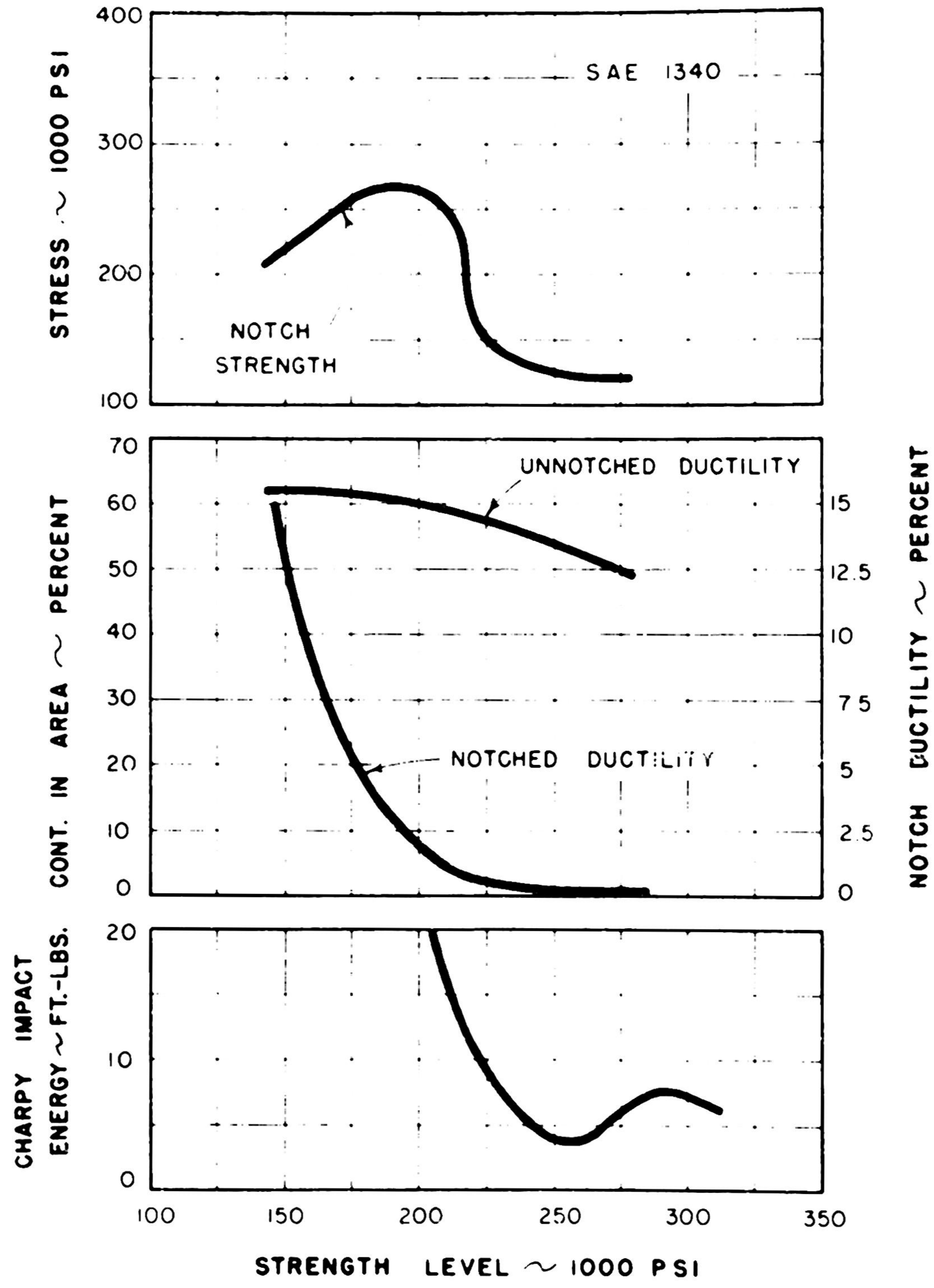

FIG. 1: EFFECT OF STRENGTH LEVEL ON SOME NOTCHED AND UNNOTCHED PROPERTIES OF STEEL.

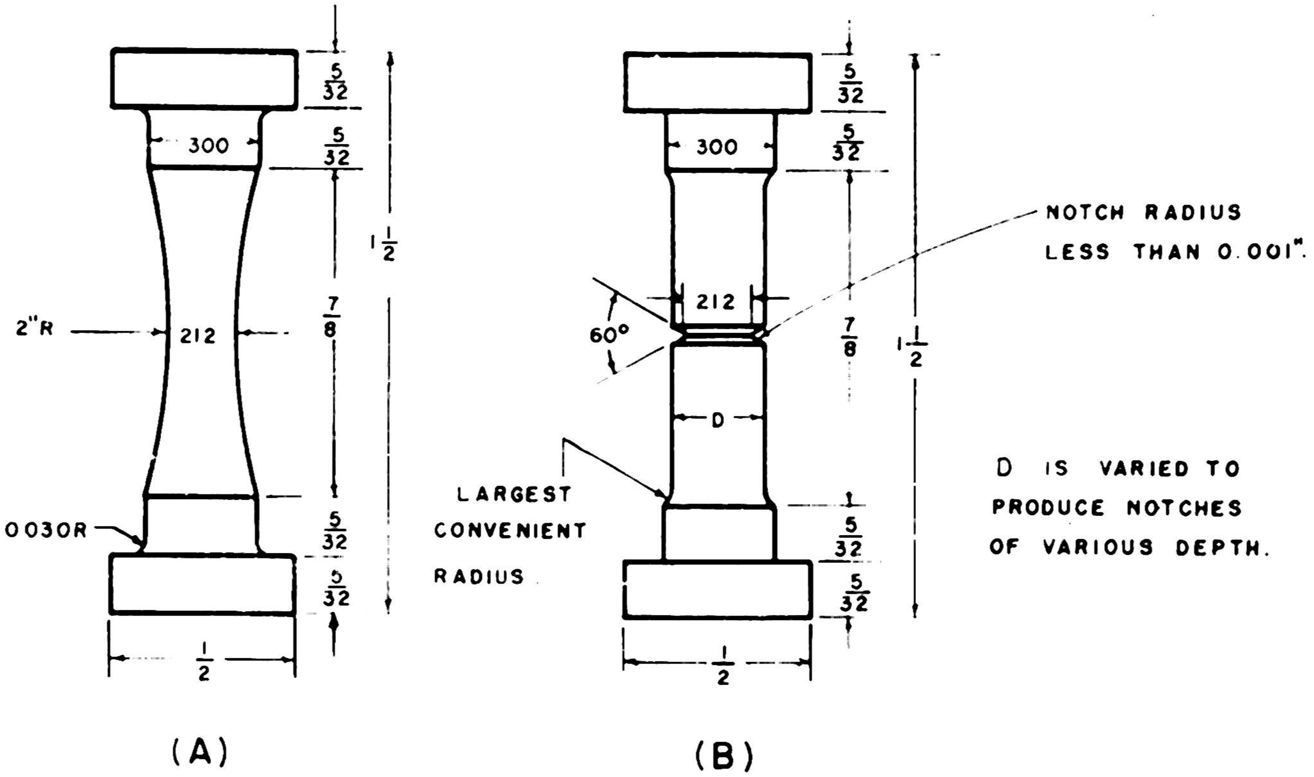

FIG. 2: TEST SPECIMENS.

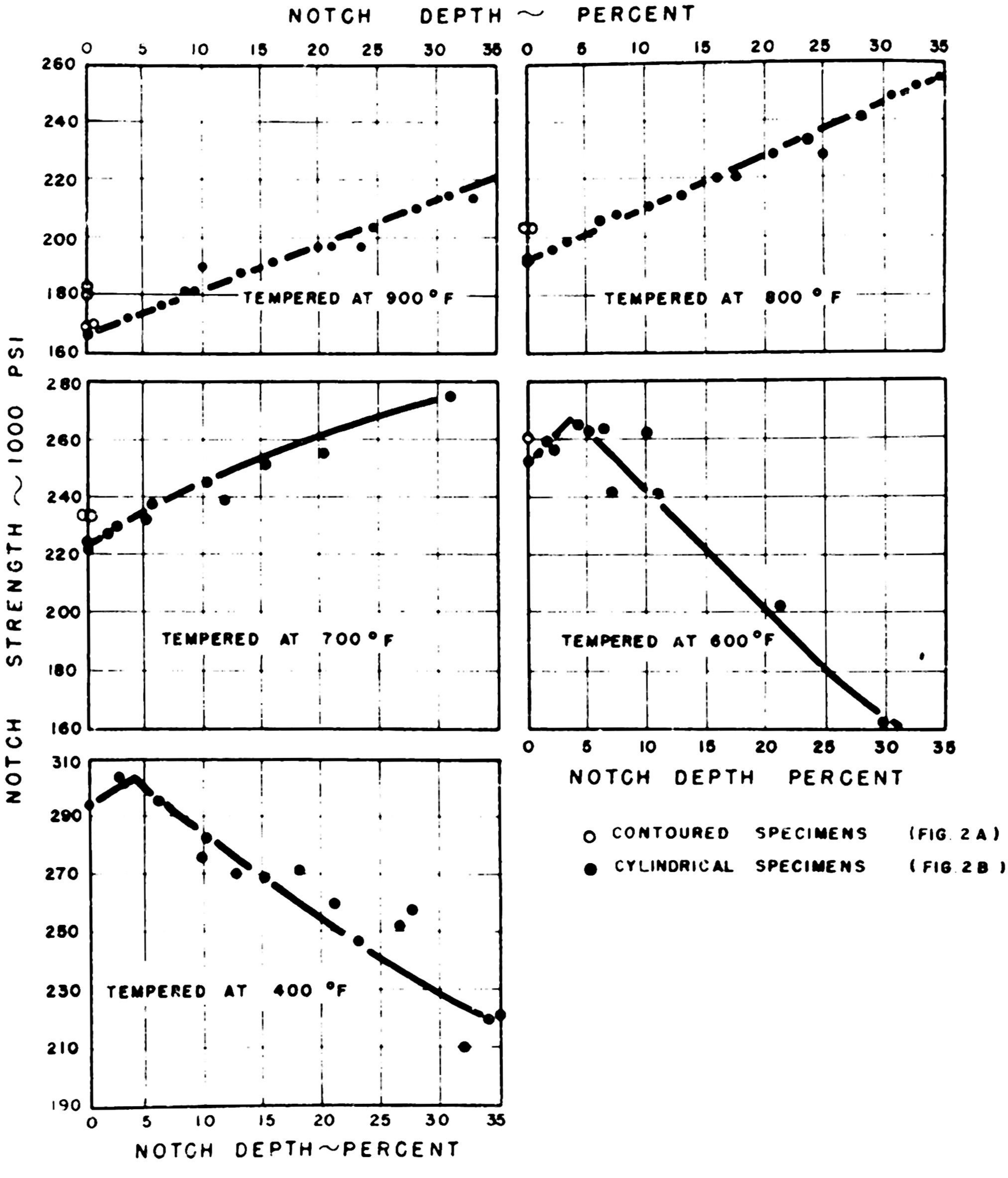

FIG. 3: EFFECT OF NOTCH DEPTH ON ROOM TEMPERATURE NOTCH STRENGTH OF SAE 1340 QUENCHED AND TEMPERED AT INDICATED TEMPERATURES.

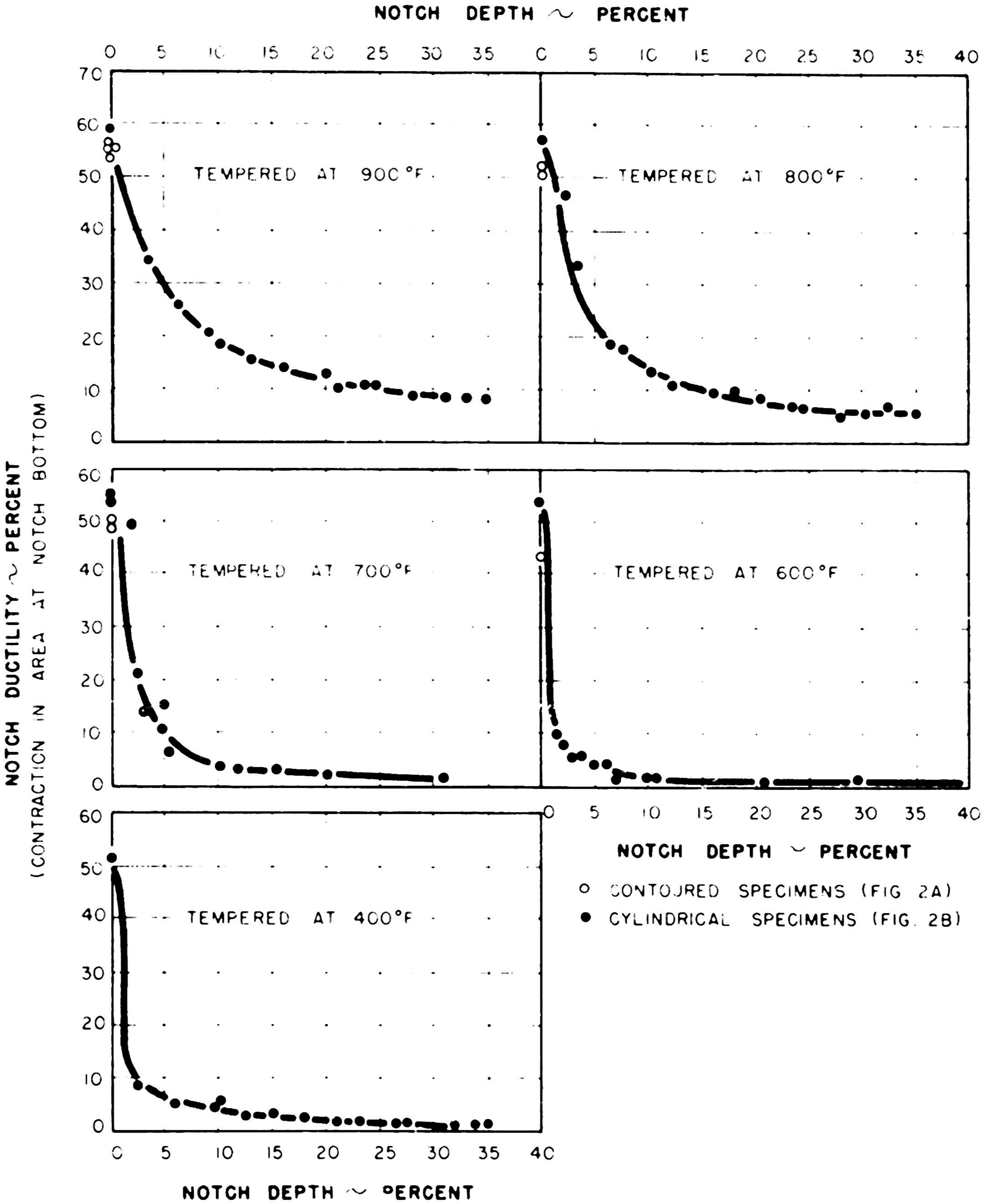

FIG. 4: EFFECT OF NOTCH DEPTH ON THE ROOM TEMPERATURE NOTCH DUCTILITY FOR SAE 1340 QUENCHED AND TEMPERED AT INDICATED TEMPERATURES.

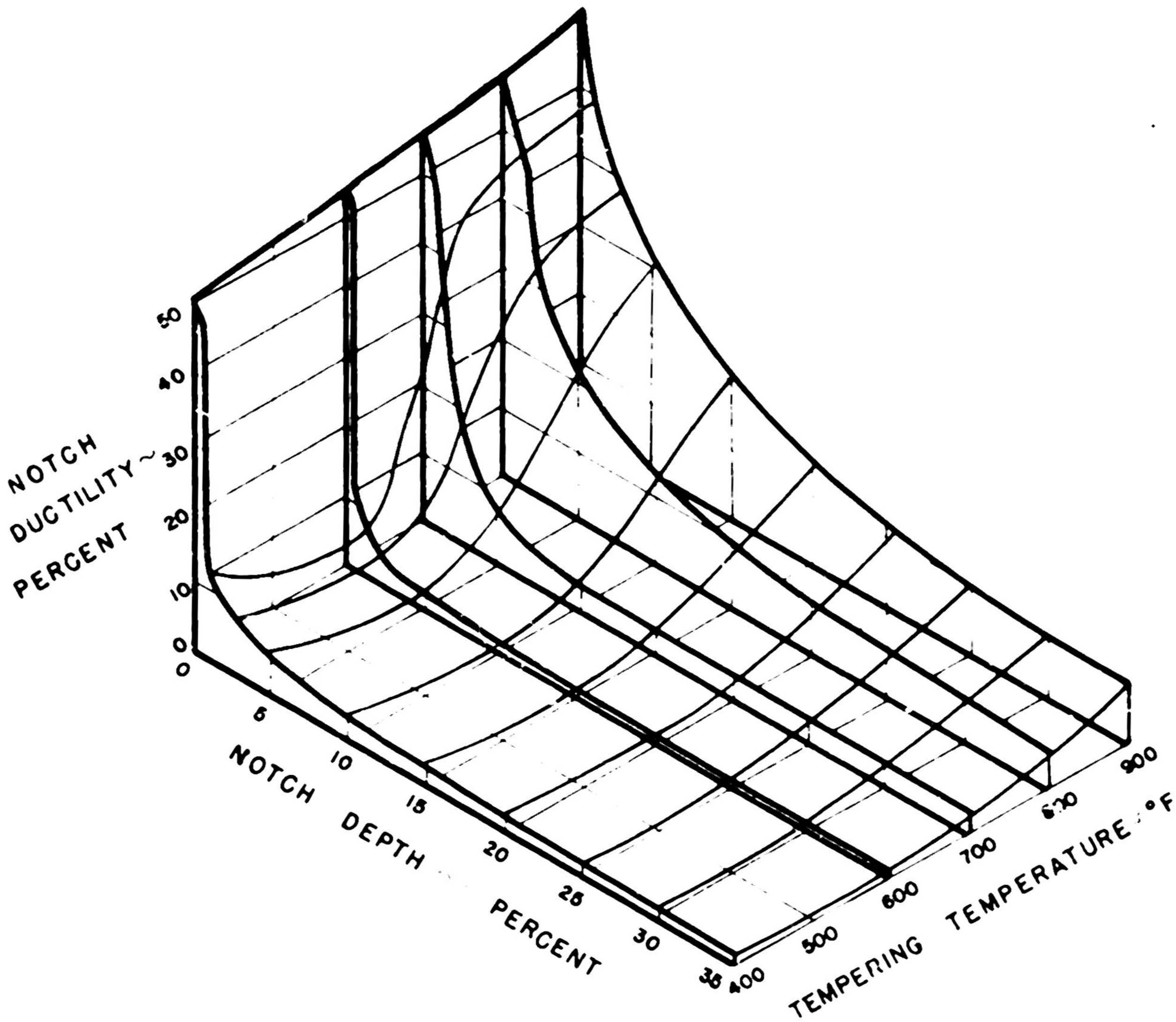

FIG. 5: SUMMARY CURVE RELATING NOTCH DUCTILITY TO NOTCH DEPTH & TEMPERING TEMPERATURE.

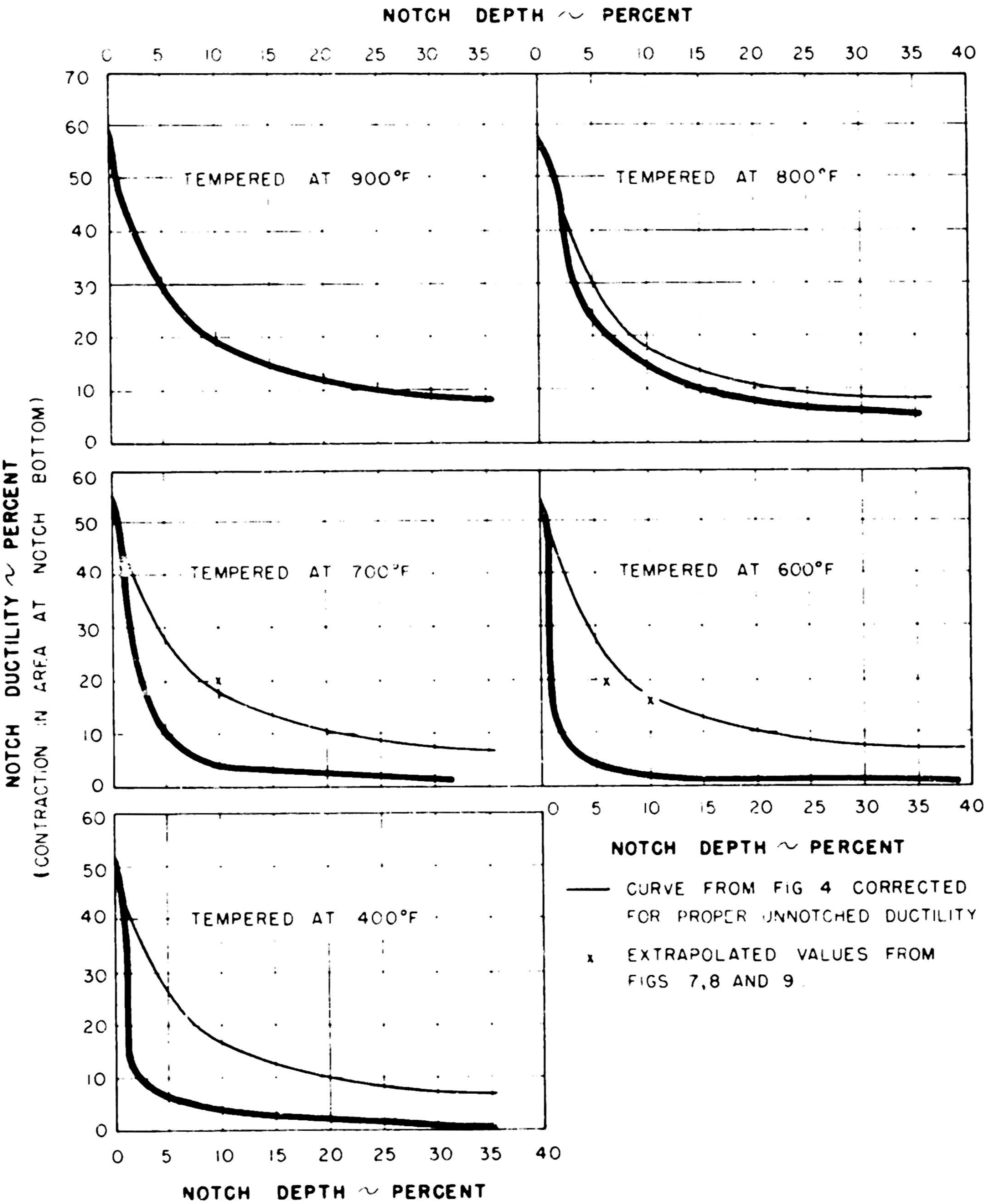

FIG. 6: COMPARISON OF THE NOTCH DUCTILITY OF SAE 1340 TEMPERED AT 900°F WITH THE DUCTILITY OBTAINED AT LOWER TEMPERING TEMPERATURES.

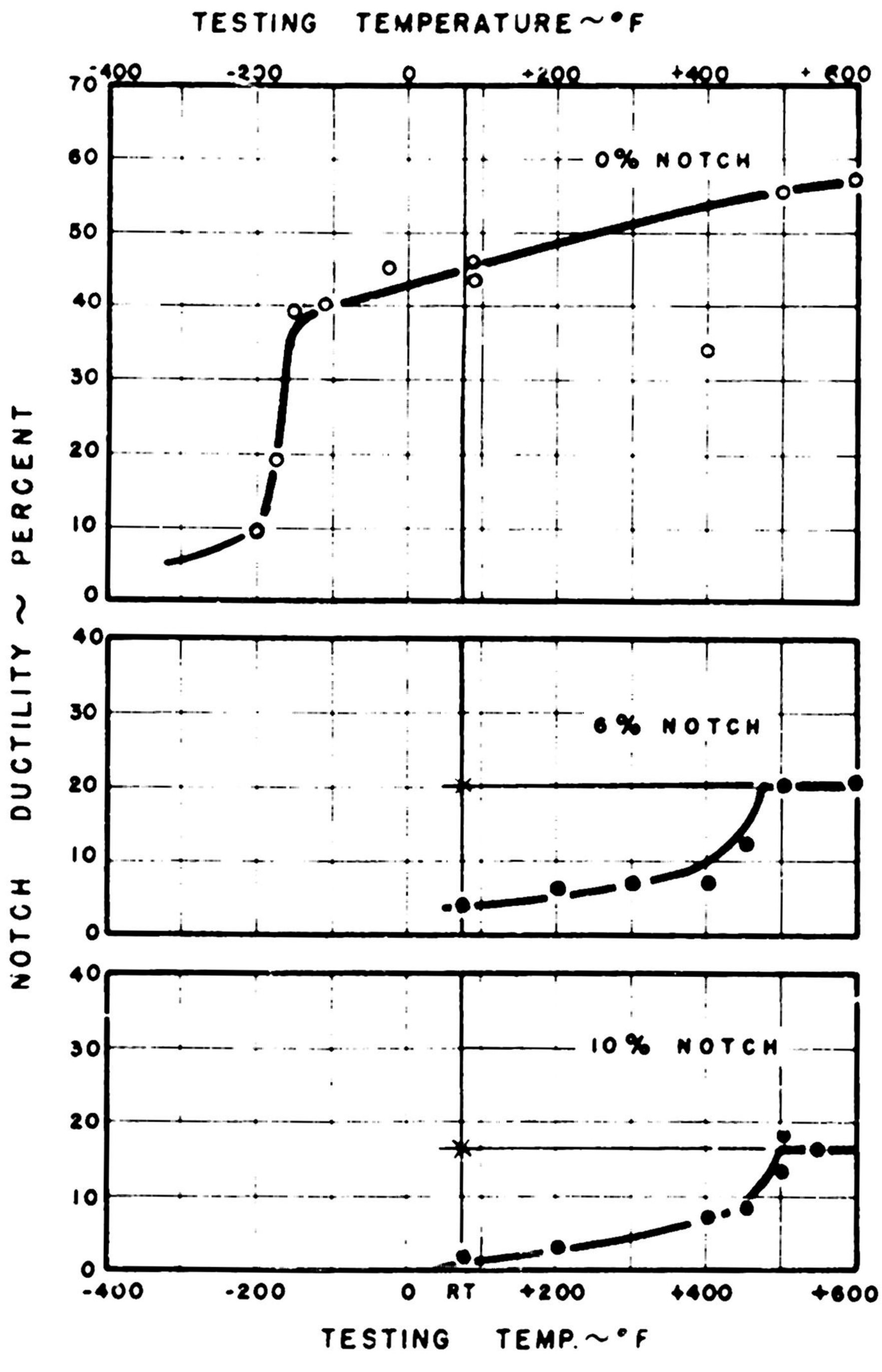

FIG. 7 : EFFECT OF NOTCH DEPTH ON TRANSITION TEMPERATURE FOR SAE 1340 QUENCHED & TEMPERED AT 600 °F

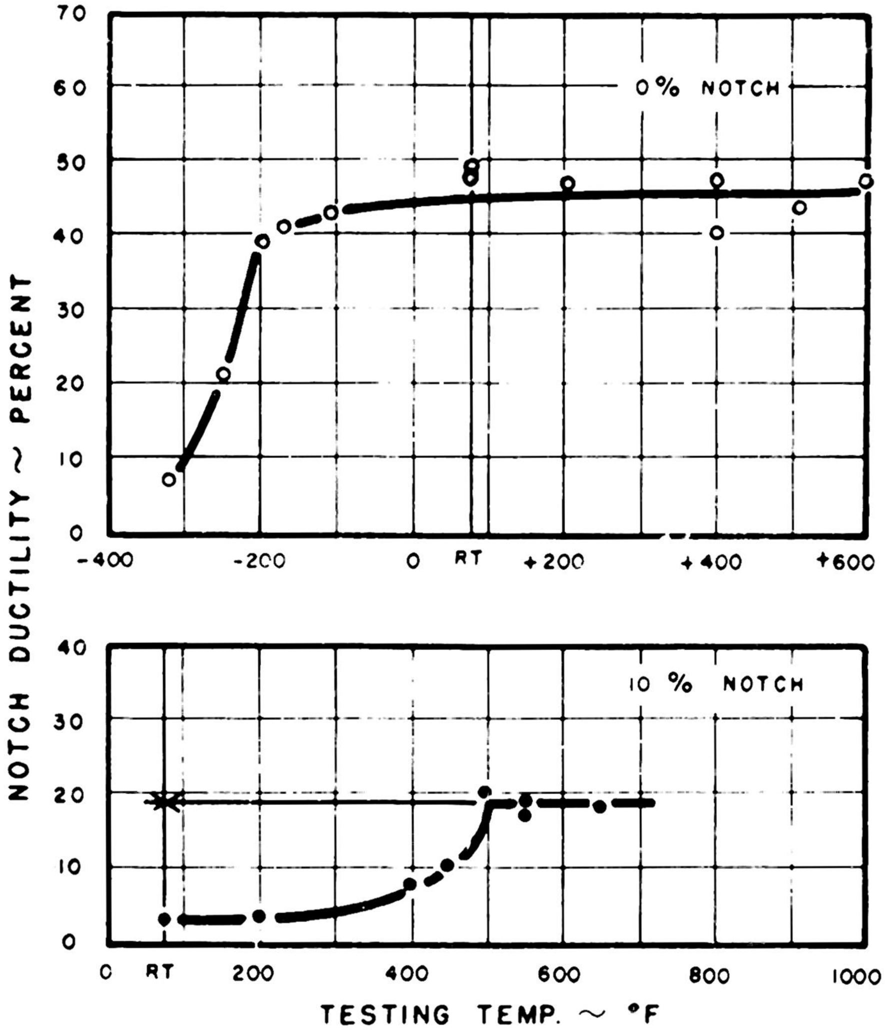

FIG. 8: EFFECT OF NOTCH DEPTH ON TRANSITION TEMPERATURE FOR SAE 1340 QUENCHED AND TEMPERED AT 700 °F.

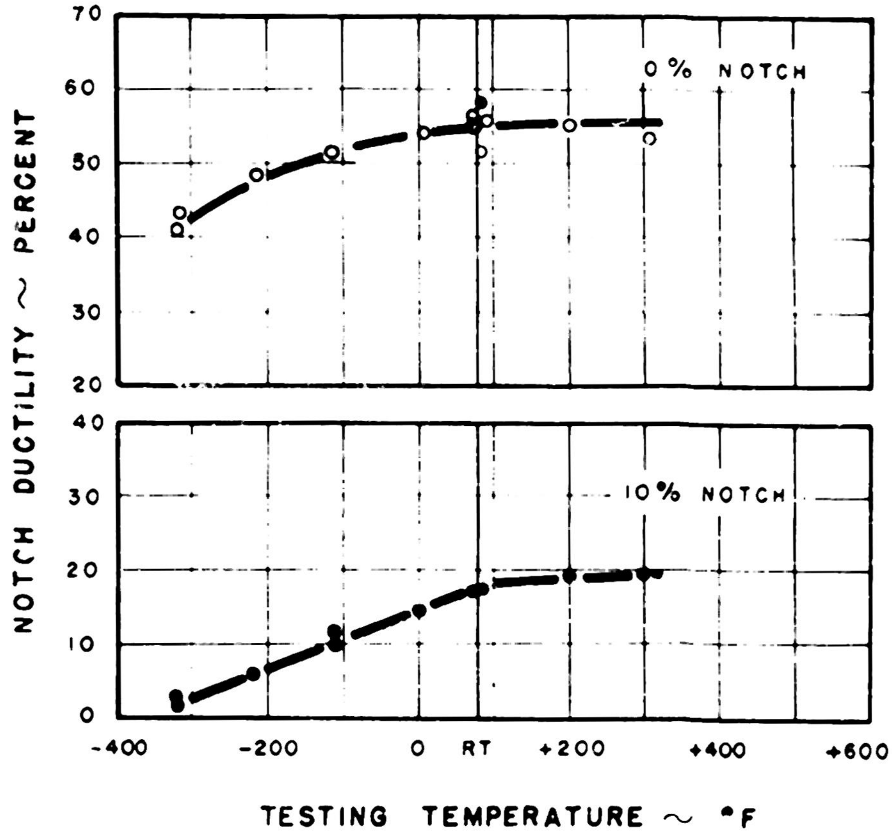

FIG. 9: EFFECT OF NOTCH DEPTH ON TRANSITION TEMPERATURE FOR SAE 1340 QUENCHED AND TEMPERED AT 900 °F.